Research on the Optimization the Structural Parameters of Mechanical Treadmill

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Abstract: This paper proposed a three-dimensional model of treadmill, structural diagram of mechanical transmission, structural optimization model and kinematic analysis model, deriving the values of connecting rods as 0.425 m, 1.673 m and 0.662 m by solving the optimization model. It further conducts a kinematic analysis on treadmill using this set of parameters and kinematic simulation software "Motion", providing simulation curves of angular displacement, angular velocity and angular acceleration of the main moving parts such as the connecting rods, pedals and handrail handles. The simulation curves indicate that when the rotation speed of the wheels is 10 r/min, the connecting rods, pedals and handrail handles move smoothly and change almost sinusoidally; the displacement of handles ranges in-700~200 mm, the speed ranges in-400~400 mm/s, the acceleration ranges in -400~500 mm/s2, the angular change of pedals is -5°~30°, the amplitude variation of angular velocity is <25°/s and the amplitude variation of angular acceleration is <28°/s2. The above mentioned calculated prospects of the treadmill provide some reference for carrying out a quick optimization design of the treadmill.

Keywords: Kinematic analysis, Parameters optimization, Structural design, Treadmill, Three-Dimensional modeling, Structural parameters.

1. INTRODUCTION

Treadmill is one of the most popular fitness equipments [1-5], in which the mechanical treadmill is related to running fitness equipment used extensively in neighborhoods and on campuses because of its cheap price, simple structure and easy maintenance [6]. In addition, it is also widely used in medical rehabilitation, step rate coordinate training and in various other situations [7-10].

With the continuous development of production technology, requirements for mechanical performance and cost-effective resources are also increasing. Kinematic simulation analysis is of great significance for the improvement of treadmill performance, which is also an important method in the current treadmill design [11]. Optimization design method makes use of the computer to achieve the objective and optimizes the design of the treadmill structural parameters. If the treadmill is prepared for optimal performance, it can be conducive to marketing and sales. The optimization of mechanical treadmill is mainly based on kinematic optimization. Therefore, in order to optimize the design of the parameters of the treadmill by establishing the optimization model, three-dimensional model is created in three-dimensional software, simulating its kinematic performance through the kinematic simulation software which provides the simulation results curve, followed by analysis and research on the exercise and dynamics of the machine. The method used in this paper not only demonstrates the feasibility of the treadmill, but also provides some guidance with respect to the engineering design, finding the best solution. It can significantly can reduce the development costs, shorten the development cycle, improve work efficiency and greatly simplify the process of design and development strategies in the development of products, while improving the quality of products [12-15].

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2. THREE-DIMENSIONAL MODELING AND WORK PRINCIPLE

The three-dimensional model of treadmill shown in Figs. (**1** and **2**) represents the mechanical transmission system, that is constructed by the pedals, rotary handle and wheel. When the fitnessenthusiast puts his foot on the pedals to carry out up and down movement, the wheel rotates, and this movement of the wheel passes on to the rotary handle that further induces back and forth movement. Thus, the movement of pedals and rotary handle helps in promoting the movement of the fitness enthusiast on the treadmill.

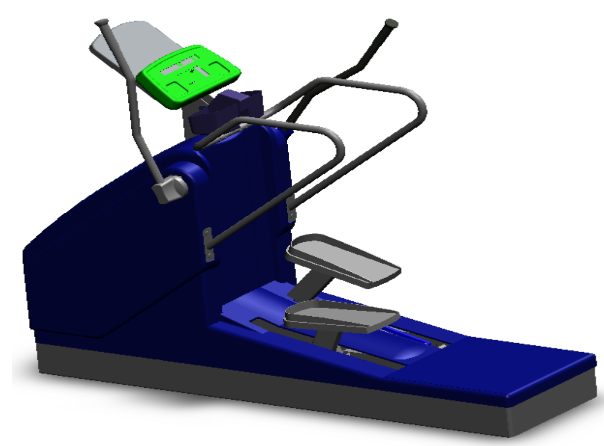

Fig. (1). Three-dimensional model of mechanical treadmill.

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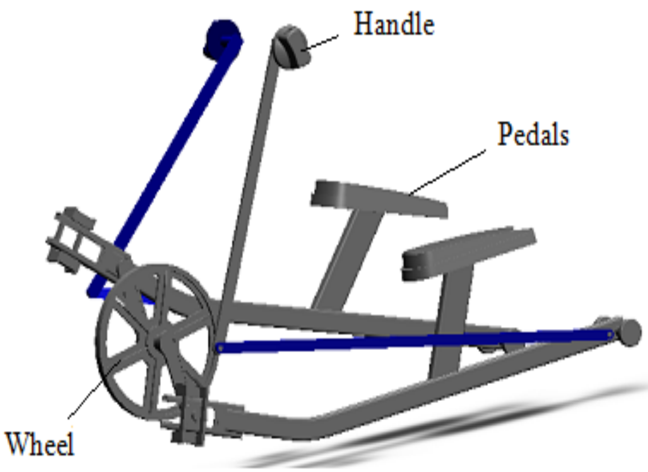

Fig. (2). Transmission system of mechanical treadmill.

3. STRUCTURAL PARAMETERS OPTIMIZATION OF TREADMILL

The structural parameters optimization of treadmill is based on its kinematic analysis For planar mechanisms, vector equation can be established according to a closed loop, where the projection equation of the vector equation represents the displacement equation of the mechanism; each vector equation can create two projection equations.

For a single closed chain mechanism consisting of n rods, the formula of closed loop vector equation is [16].

$$\sum l_i = 0 \tag{1}$$

In the formula, l_i is the i-th lever length, $i = 1,2,\cdots,n$.

The displacement equation formula of the component can be described as:

$$\begin{cases} \sum l_i \cos\varphi_i = 0 \\ \sum l_i \sin\varphi_i = 0 \end{cases} \tag{2}$$

By seeking the derivative of time t, the rate equation formula can be written as:

$$\begin{cases} \sum \dfrac{\mathrm{d}l_i}{\mathrm{d}t}\cos\varphi_i - l_i\dfrac{\mathrm{d}\varphi_i}{\mathrm{d}t}\sin\varphi_i = 0 \\ \sum \dfrac{\mathrm{d}l_i}{\mathrm{d}t}\sin\varphi_i + l_i\dfrac{\mathrm{d}\varphi_i}{\mathrm{d}t}\cos\varphi_i = 0 \end{cases} \tag{3}$$

The acceleration equation formula is:

$$\begin{cases} \sum \dfrac{\mathrm{d}^2 l_i}{\mathrm{d}t^2}\cos\varphi_i - 2\dfrac{\mathrm{d}l_i}{\mathrm{d}t}\dfrac{\mathrm{d}\varphi_i}{\mathrm{d}t}\sin\varphi_i - l_i\left(\dfrac{\mathrm{d}\varphi_i}{\mathrm{d}t}\right)^2\cos\varphi_i - l_i\dfrac{\mathrm{d}^2\varphi_i}{\mathrm{d}t^2}\sin\varphi_i = 0 \\ \sum \dfrac{\mathrm{d}^2 l_i}{\mathrm{d}t^2}\sin\varphi_i - 2\dfrac{\mathrm{d}l_i}{\mathrm{d}t}\dfrac{\mathrm{d}\varphi_i}{\mathrm{d}t}\cos\varphi_i - l_i\left(\dfrac{\mathrm{d}\varphi_i}{\mathrm{d}t}\right)^2\sin\varphi_i + l_i\dfrac{\mathrm{d}^2\varphi_i}{\mathrm{d}t^2}\cos\varphi_i = 0 \end{cases} \tag{4}$$

Assuming the unknown displacement variable $\varphi = (\varphi_1,\varphi_2,\cdots,\varphi_n)$, known input $q = (q_1,q_2,\cdots,q_n)$, thus the displacement equation is often simplified as follows

$$f(\varphi,q) = 0, \tag{5}$$

The velocity equation can be written as:

$$[A][\dot{\varphi}] = [B][\dot{q}] \tag{6}$$

$$[\dot{\varphi}] = [\dot{\varphi}_1,\dot{\varphi}_2,\cdots,\dot{\varphi}_n]^{\mathrm{T}} \tag{7}$$

$$[\dot{q}] = [\dot{q}_1\dot{q}_2,\cdots,\dot{q}_n]^{\mathrm{T}} \tag{8}$$

In the formula, $[A]$ is the driven member position parameters matrix and which equals with the Jacobian matrix in form, by just changing x_i to φ_i; $[B]$ is the active member position of parameters matrix or matrix known parameters.

The acceleration matrix equation:

$$[A][\ddot{\varphi}] = [B][\ddot{q}] + [B][\dot{q}] - [\dot{A}][\dot{\varphi}] \tag{9}$$

Similar to the kinematic analysis of plane mechanism, the spatial kinematic analysis also includes the analysis of displacement, velocity and acceleration. In accordance with the movement relations between the active member and the driven member, the motion displacement equation simplifies to:

$$F(\varphi,\psi) = 0 \tag{10}$$

In the formula, φ, ψ is respectively the angular displacement of the driven member and the active member.

By seeking the derivative of the displacement equation as described in formula (10), the velocity equation can be obtained as

$$\frac{\partial F}{\partial \varphi}\dot{\varphi} + \frac{\partial F}{\partial \psi}\dot{\psi} = 0 \tag{11}$$

The velocity equation is a linear equation and on solving the unknown velocity $\dot{\psi}$, and seeking its derivation, the acceleration equation can be obtained:

$$\frac{\partial^2 F}{\partial \varphi^2}\dot{\varphi}^2 + \frac{\partial F}{\partial \varphi}\ddot{\varphi} + 2\frac{\partial^2 F}{\partial \varphi \partial \psi}\dot{\psi}\dot{\varphi} + \frac{\partial^2 F}{\partial \psi^2}\dot{\psi}^2 + \frac{\partial F}{\partial \psi}\ddot{\psi} = 0 \tag{12}$$

This acceleration equation is also a linear equation.

In order to optimize and analyze easily, we simplified Fig. (**2**) to crank rocker mechanism as shown in Fig. (**3**), where the design variables represent the length of each rod.

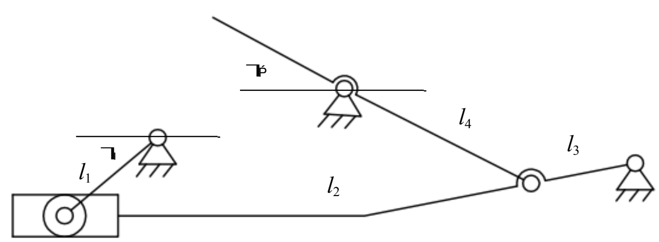

Fig. (3). Transmission system equivalent diagram of mechanical treadmill.

Assuming the function formula between the rotation angle θ_i ($i = 2,3,4$) of other components and the rotation angle θ_1 of input component,

$$\theta_i = f(l_1,l_2,l_3,l_4,\theta_1) \tag{13}$$

In the formula, l_1, l_2, l_3, l_4 are transmission system connecting rod lengths of mechanical treadmill; θ_1, θ_2, θ_3, θ_4 are the intersection angles that the connecting rod is relative to the horizontal position.

Obtained by the formula (9), when the rotation angle of input component is θ_1, the rotation angle θ_i of output component can be calculated by the following formula:

$$\theta_i = \beta_0 + \delta_0 - \beta_1 - \delta_1 \tag{14}$$

In the formula,

$$\beta_0 = \arctan\frac{l_1\sin\theta_0}{1-l_1\cos\theta_0} \quad \delta_0 = \arccos\frac{l_1^2-l_2^2+l_3^2+1-2l_1\cos\theta_0}{2l_3\sqrt{l_1^2+1-2l_1\cos\theta_0}}$$

$$\beta_1 = \arctan\frac{l_1\sin(\theta_0+\theta_{0i})}{1-l_1\cos(\theta_0+\theta_{0i})}$$

$$\delta_1 = \arccos\frac{l_1^2-l_2^2+l_3^2+1-2l_1\cos(\theta_0+\theta_{0i})}{2l_3\sqrt{l_1^2+1-2l_1\cos(\theta_0+\theta_{0i})}}$$

where, θ_0 is the initial angle of the connecting rod l_1; and θ_{0i} is the increased amount of angle of the connecting rod l_1, that is $\theta_1 = \theta_0 + \theta_{0i}$.

Further expression of formula (13) is [17]:

$$\begin{aligned} f(l_1,l_2,l_3,l_4,\theta_1) &= \arctan\frac{l_1\sin\theta_0}{1-l_1\cos\theta_0} + \arccos\frac{l_1^2-l_2^2+l_3^2+1-2l_1\cos\theta_0}{2l_3\sqrt{l_1^2+1-2l_1\cos\theta_0}} \\ &-\arctan\frac{l_1\sin(\theta_0+\theta_{0i})}{1-l_1\cos(\theta_0+\theta_{0i})} - \arccos\frac{l_1^2-l_2^2+l_3^2+1-2l_1\cos(\theta_0+\theta_{0i})}{2l_3\sqrt{l_1^2+1-2l_1\cos(\theta_0+\theta_{0i})}} \end{aligned} \tag{15}$$

It can be known from Fig. (**3**) that the design variables of mechanical treadmill are the length of each connecting rod; the optimization design goal of mechanism is to enable the minimum error between the rotation angle of output component and the given θ_{di} in all positions, setting the objective function [18] as,

$$F(\boldsymbol{x}) = \sum_{i=1}^{3}\omega_i\left[f(l_1,l_2,l_3,l_4,\theta_1) - \theta_{di}\right]^2 \tag{16}$$

where, ω_i is the penalty factor. The constraints of mechanism optimization design should be determined according to the actual situation of institutional design. For example, the crank rocker four-bar linkage must satisfy the following relationship [19].

$$\begin{cases} l_1 + l_2 \le l_3 + l_4 \\ l_1 + l_3 \le l_2 + l_4 \\ l_1 + l_4 \le l_2 + l_3 \end{cases} \tag{17}$$

If the mechanism requires flexible and reliable transmission, then the transmission angle γ should satisfy:

$$[\gamma]_{\min} \le \gamma \le [\gamma]_{\max} \tag{18}$$

Among them

$$\cos\gamma_i = \frac{l_2^2+l_3^2-l_1^2-1+2l_1\cos(\theta_0+\theta_{0i})}{2l_2l_3}$$

From the above equation, the transmission angle γ_i changes with the change in $\theta_0+\theta_{0i}$; when $\cos(\theta_0+\theta_{0i})$ is maximum, γ_i is minimum, and when $\cos(\theta_0+\theta_{0i})$ is minimum, γ_i is maximum. To satisfy the above conditions, the constraint equation should be:

$$\begin{cases} \cos[\gamma]_{\min} - \dfrac{l_2^2+l_3^2-l_1^2-1+2l_1\left[\cos(\theta_0+\theta_{0i})\right]_{\max}}{2l_2l_3} \ge 0 \\ \dfrac{l_2^2+l_3^2-l_1^2-1+2l_1\left[\cos(\theta_0+\theta_{0i})\right]_{\min}}{2l_2l_3} - \cos[\gamma]_{\min} \ge 0 \end{cases} \tag{19}$$

The crank rocker mechanism has [20]

$$\begin{cases} \left[\cos(\theta_0+\theta_{0i})\right]_{\max} = 1 \\ \left[\cos(\theta_0+\theta_{0i})\right]_{\min} = -1 \end{cases} \tag{20}$$

Therefore, the constraint equation is:

$$\begin{cases} \cos[\gamma]_{\min} - \dfrac{l_2^2+l_3^2-(1-l_1)^2}{2l_2l_3} \ge 0 \\ \dfrac{l_2^2+l_3^2-(1+l_1)^2}{2l_2l_3} - \cos[\gamma]_{\max} \ge 0 \end{cases} \tag{21}$$

Assuming that the rotation angle of input component is divided into 20 equal portions, taking the right factor $\omega_i = 1$, l_4 and other connecting rods are not in a chain link, having little impact on other parameters, then the connecting rod $l_4 = 1$ setting $\boldsymbol{x} = [x_1, x_2, x_3] = [l_1, l_2, l_3]$, thus the optimization objective function of crank link mechanism can be obtained by equation (16) and (15) as follows,

$$\min F(x) = \sum_{i=2}^{4}\omega_i\left[\begin{aligned} &\arctan\frac{x_1\sin\theta_0}{1-x_1\cos\theta_0} + \arccos\frac{x_1^2-x_2^2+x_3^2+1-2x_1\cos\theta_0}{2x_3\sqrt{x_1^2+1-2x_1\cos\theta_0}} - \arctan\frac{x_1\sin(\theta_0+\theta_{0i})}{1-x_1\cos(\theta_0+\theta_{0i})} \\ &-\arccos\frac{x_1^2-x_2^2+x_3^2+1-2x_1\cos(\theta_0+\theta_{0i})}{2x_3\sqrt{x_1^2+1-2x_1\cos(\theta_0+\theta_{0i})}} - \frac{6}{\pi}\sin\left(\frac{\pi\theta_{0i}}{180^\circ}\right) \end{aligned}\right]^2 \tag{22}$$

The optimization design constraints are as follows [21]

$$\begin{cases} 1 - x_1 - x_2 + x_3 \ge 0 \\ 1 - x_1 + x_2 - x_3 \ge 0 \\ -1 - x_1 + x_2 + x_3 \ge 0 \end{cases} \tag{23}$$

Required that transmission angle meets $30^\circ \le \gamma \le 135^\circ$, the equation (23) becomes:

$$\begin{cases} \dfrac{\sqrt{3}}{2} - \dfrac{x_2^2+x_3^2-(1-x_1)^2}{2x_2x_3} \ge 0 \\ \dfrac{x_2^2+x_3^2-(1-x_1)^2}{2x_2x_3} - \dfrac{\sqrt{2}}{2} \ge 0 \end{cases} \tag{24}$$

According to the mechanism structure size, each component length relatively to the length of chassis is within a given size range, thus on the basis of demand, we can get

$$\begin{cases} 0.1 \le x_1 \le 1 \\ 1 \le x_2 \le 3 \\ 0.5 \le x_3 \le 1 \end{cases} \quad (25)$$

Interior point penalty function method is used for the solution. Selecting the initial penalty parameter $\gamma_0 = 0.001$, the initial point $\boldsymbol{x} = [x_1, x_2, x_3] = [1,3,1]$, taking the penalty function convergence precision as 0.001, the optimal solution is:

$$\boldsymbol{x}^* = [0.425, 1.673, 0.662] \quad (26)$$

It can be seen from the optimization results that the transmission system connecting rods of mechanical treadmill are respectively 0.425 m, 1.673 m and 0.662 m.

4. KINEMATIC ANALYSIS OF MECHANICAL TREADMILL

By using the software "Motion" to simulate the kinematics, we can obtain the displacement, velocity and acceleration parameters of the connecting rods, pedals and the handrail handles when the wheel is at rotational velocity of 10r/min. The specific simulation curves of connecting rods are shown in Figs. (**4-6**).

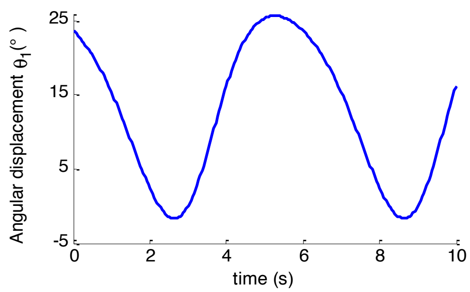

Fig. (4). The angular displacement of connecting rods.

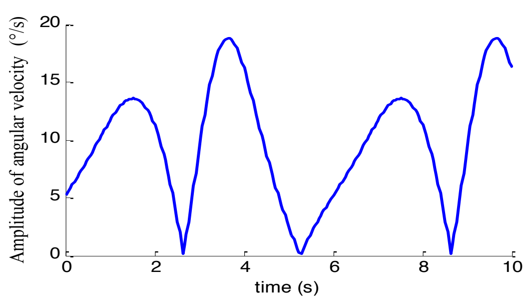

Fig. (5). The angular velocity of connecting rods.

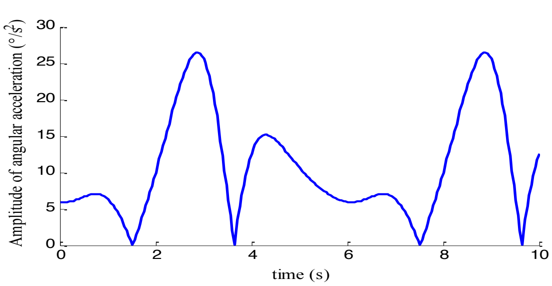

Fig. (6). The angular acceleration of connecting rods.

The simulation curves of pedals shown in Figs. (**7-9**).

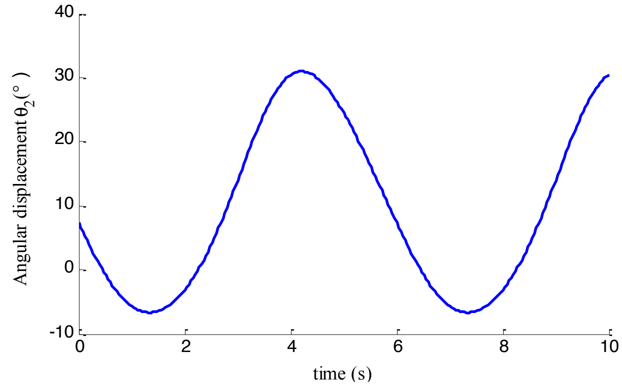

Fig. (7). The angular displacement of pedals.

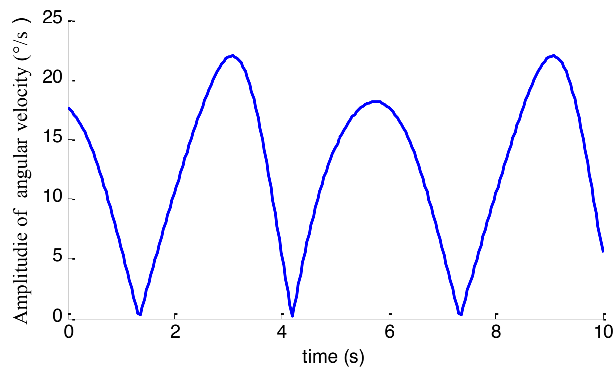

Fig. (8). The angular velocity of pedals.

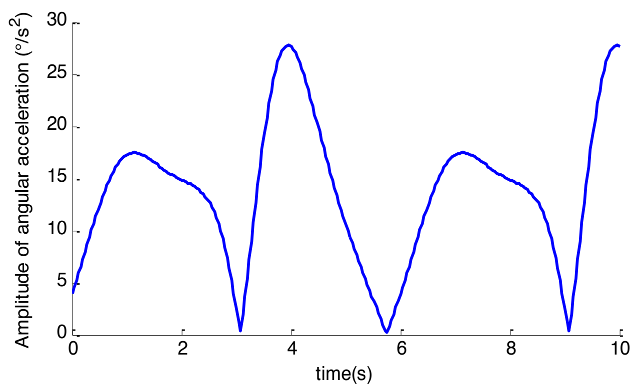

Fig. (9). The angular acceleration of pedals.

The simulation curves of handrail handles are shown in Figs. (**10-12**).

When the wheel is at the rotational speed of 10 r/min, it can be known from the above simulation curves that the connecting rods, pedals and handrail handles motion smoothly, almost in a sinusoidal variation, and the main design parameters such as the displacement of handles are in ranges -700~200 mm, the velocity ranges are -400~ 400 mm/s, the acceleration ranges are -400~500 mm/s2, the angular change of pedals is -5°~30°, the amplitude variation of angular velocity is <25°/s and the amplitude variation of angular acceleration is <28°/s2. This study therefore provides some reference to the quick optimization design of mechanical treadmill.

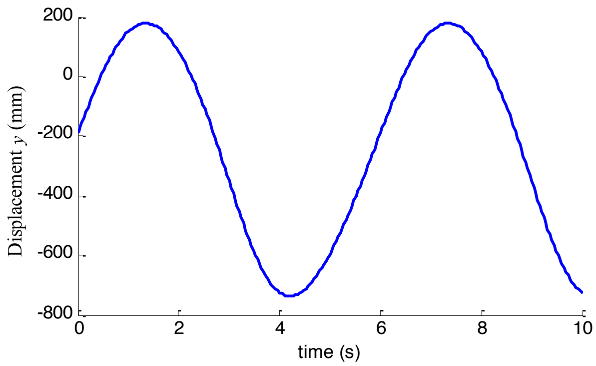

Fig. (10). The displacement of handrail handles.

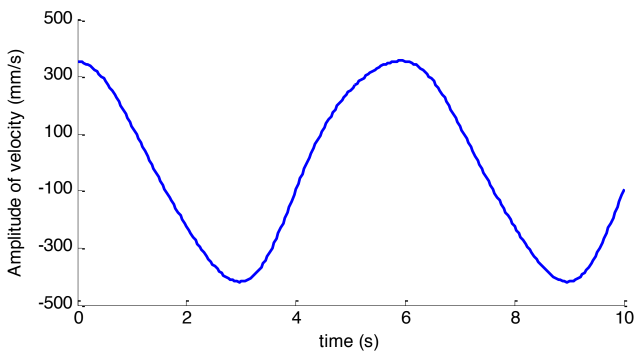

Fig. (11). The speed of handrail handles.

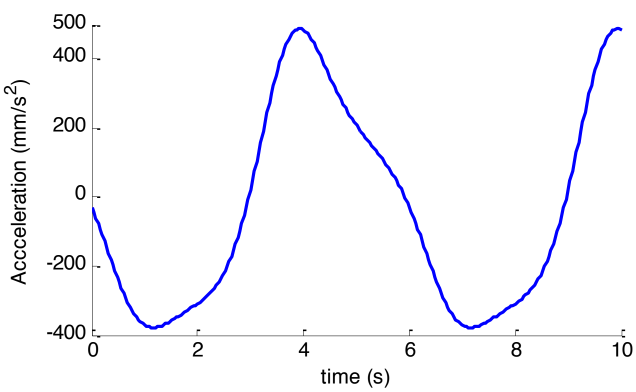

Fig. (12). The acceleration of handrail handles.

CONCLUSION

Through the parameters of optimization and kinematic simulation of mechanical treadmill, we obtained the design parameters of mechanical treadmill and the simulation curves of angular displacement, angular velocity and angular acceleration of the major moving parts, having several main conclusions as follows:

1) When the length values of connecting rods are 0.425 m, 1.673 m, 0.662 m, and 1 m, the treadmill gives the best performance;

2) Based on the above optimization parameters, by conducting kinematic analysis for the treadmill and extracting the simulation curves of each optimized component, it is known that the connecting rods, pedals and handrail handles motion smoothly, almost in a sinusoidal variation, and can provide the best service for to the fitness enthusiast.

3) The displacement of handles ranges are -700~200 mm, the speed ranges from -400~400 mm/s, the acceleration ranges from -400~500 mm/s2, the angular change of pedals is -5°~30°, the amplitude variation of angular velocity is <25°/s and the amplitude variation of angular acceleration is <28°/s2.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

Declared none.

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Received: February 17, 2014 Revised: March 21, 2015 Accepted: June 9, 2015